Fermilab

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# Magnet Field Measurements on Cooling Ring Dipoles

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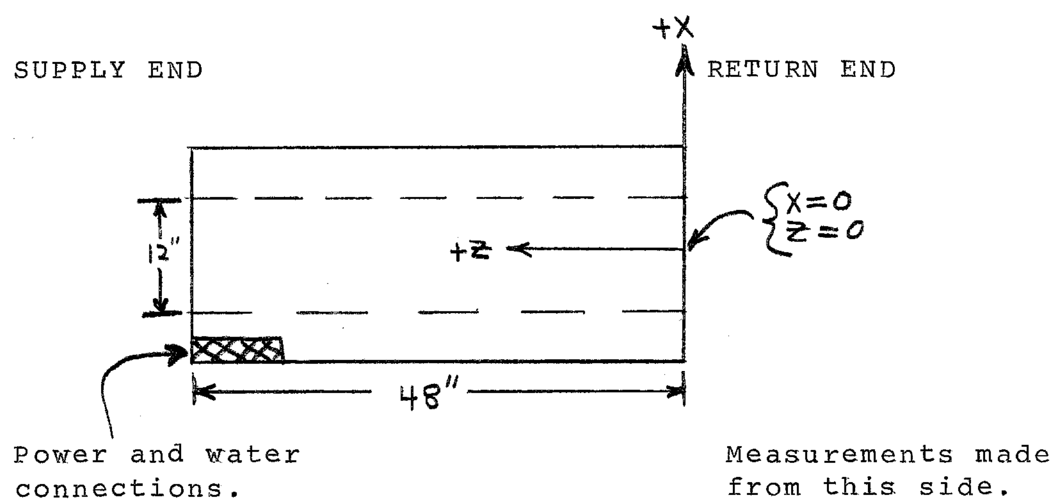
Field measurements were made on cooling ring dipoles #1002 and #1003. The magnets have a aperture gap of 3.25" and an aperture width of 12". They are 48" long from one lamination face to the other lamination face and contain 40 turns of current carrying conductor. The typical paramenters are listed in Table 1.

## 1. Magnet Orientation

All measurements were made from the return end of the magnet. Shown below is a top view of the magnet and the selected coordinate system.




Top View Looking down.

## 2. B vs I

An NMR was used to measure the magnetic field at center as a function of current, and the data is shown in Figure 1. Table 2 lists the measurement results on dipoles #1002 and #1003. Figure 2 is a plot of the transfer function versus current for magnets #1002 and #1003. This clearly shows the saturation effect above 800 Amperes. Below 500 Amperes the field of Magnet #1003 is higher than that of Magnet #1002 by 0.1%, but that difference becomes negligible above 550 Amperes. The difference at low fields is due to loose clamping between top and bottom cores. At higher fields the magnetic force pulls the half cores together, hence reducing the field difference between the two magnets.

If there is 1 mil extra back leg gap, then the gap height is larger by 1 mil. This will cause the variation of the central field by $6 \times 10^{-4}$. The variation of 1 mil in back leg gap is expected in production magnets.

## 3. $\int$Bdl vs I

A two turn stretched wire probe was used to measure the integrated magnetic field as function of current. Table 3 gives the measurement results for magnet #1003. Figure 3 is a plot of the integrated field versus current. It shows a saturation effect above 700 amperes. The integrated magnetic field is a function of central field and the length of the magnet. A variation of one lamination thickness (1/16") will change the integrated field by $1 \times 10^{-3}$. Any lamination bulging at the end faces of the magnet will also affect the integrated field in the same way.

TABLE 3

| CURRENT (Amperes) | B dl (KG-m) |
|---|---|
| 0.0 | .009 |
| 200.8 | 1.592 |
| 402.0 | 3.186 |
| 602.6 | 4.767 |
| 803.2 | 6.294 |
| 904.2 | 6.981 |
| 1004.6 | 7.597 |
| 1104.3 | 8.145 |
| 1205.0 | 8.641 |

## 4. Central Field Shape

A Hall Probe was placed deep inside magnet #1002 and then moved from side to side. Figure 4 is a plot of remanent field (Gauss) versus position. The remanent field is about 7.7 Gauss at center, and shows a big sextupole term. The variation in the remanent field value is expected to be about $\pm$ 1 Gauss due to the variation of coercive force. The remanent field drops by 1.6 Gauss at $\pm$ 4 inches.

Figure 5 shows the percent change in field as a function of position for a field of 480 Gauss and for a field of 5 KG. The field at 5 KG is flat out to $\pm$ 4 inches. The field at 480 G shows a drop of about 0.1%, which is 0.5 G. This is related to the remanent field droop of 1.6 G.

5. Field Shape at 5 KiloGauss

The cooling ring dipoles have been designed to operate at a nominal field of 5 kiloGauss. The quality of the central field was found by, placing a 2' long search coil in the center of magnet #1003 and then moving it from side to side. The field deep inside the magnet is very flat, as shown in Table 4 and Figure 6.

The total integrated field shape was found by placing a long stretched wire probe through the magnet and then moving it from side to side. As table 4 and Figure 6 show the integrated field without shims is not as flat as desired.

To compensate for the undesirable end effects a variety of shimming schemes were tried on the beveled ends of the pole tips. The final shim arrangement consists of placing one 7/8" x 1¼" x 1/16" shim on each corner of the beveled surface. The stretched wire measurement was repeated and the integrated field was found to be very flat, as shown in Table 4 and Figure 6.

If the back leg gap on one side of the magnet is 1 mil larger than the other side, the field will change by $1 \times 10^{-4}$ over an 8 inch width.

6. Fringe Field Measurements and Effective Magnetic Length

A Hall Probe mounted on a lathe was used to measure how rapidly the field falls off outside the magnet. The fringe field was measured at Ø Amperes, 80 Amperes (480 gauss) and at 854 Amperes (5 KG). Figure 6 shows this data. At 5 KG the effective magnetic edge is 1.74 inches outside the edge of steel laminations, as was calculated from Figure 7. The effective magnetic length was calculated at 5 KG, using stretched wire data and it was found to be 51.64 inches, which is 3.64 inches over the core length of 48 inches.

7. Inductance

Inductance was measured at frequencies of 1 KHz and 50 Hz.

The current level used for both measurements was 1.6 Amperes.

At 1 KHz, $L_s = 9.4mH$ At 50 Hz, $L_s \doteq 10.53mH$

$Q \doteq 8.4$ $Q = 15.5$

8. Water Flow

Pressure in $\doteq$ 150 psi

Pressure out = 12 psi

Flow rate = 5.8 gpm

It was noted that even at 1000 amperes the magnet coil windings remained relatively cool

9. Notes on Proposed Production Measurements

Detailed measurements such as were done on cooling ring dipoles #1002 and #1003 are not practical for production testing. A simple and yet accurate way of determining if a magnet is acceptable is to compare the field in the magnet under test to that of a standard or reference cooling ring dipole.

This consists of placing a long search coil in the reference magnet (in series with magnet under test) and a similar search coil in the magnet being tested. The signals from each search coil are electrically bucked against one another and the resultant signal is nearly zero.

Three search coils for this purpose have been made (one is a spare). They are each 84" long by 1" wide and contain 10 turns of #36 wire and are made of G-10.

Micarta mounting plates that fit into the cooling ring magnets have also been designed. They have machined grooves into which the long search coils may be accurately positioned. The possible error due to tilting of the search coil is much less than one degree. This corresponds to a measuring error of less than 1 part in $10^4$.

10. Equipment List

**Transrex 500-5 power supply, Fermilab 311566**

Transductor calibration : 1000 amperes = 1.99213 volts

Acme 22.5 KW power supply, Fermilab #3271

Empro 100 Amp/100 mv shunt (.25%)

Spectromagnetics Model 5300 NMR, Fermilab #17447

F.W. Bell Gaussmeter, Model 811AR, Fermilab #10864

F.W. Bell Hall Probe, Model T-8860-138 (.25%), Serial #109401

Magnetic Measurements "Booster" Integrator

$R_{int} = 9955.3\ \Omega$ (stretched wire probe)

$C_{int} = 1\mu f \pm .1\%$

| | | |
|---|---|---|
| Stretched wire flip coil: | 2 turns of 4 mil diameter tungsten Wire separated by .500" quartz spacer $R = 118\ \Omega$ | |
| Search coil: | 48" x ½" x 9 turns | $(20\Omega)$ |
| Search coil | 24" x 1" x 4 turns | $(5\Omega)$ |
| Bucking coil: | 32" x 1-3/4" x 2 turns | $(.6\Omega)$ |

Dana Model 5900 D.V.M., Fermilab #23445

Dana Model 5900 D.V.M.. Fermilab #21796

General Radio Inductance Bridge, Model 1633-A, Fermilab #10826

Simpson Model 260 Multimeter

TABLE 1

<u>Cooling Ring Dipole Characteristics</u>

| | |
|---|---|
| Length: | 48" |
| Lamination Outside Dimensions: | 22" x 10" |
| Lamination Thickness: | 1/16" |
| Gap Height: | 3.25" |
| Gap Width: | 12" |
| Turn Number: | 40 |
| Water Flow: | 5.8 gpm at 150 psi |
| Magnet Weight: | 2500 lbs. |
| Designed Field: | 5 KG at 821 Amp. D.C. |
| $\int B\,dl =$ | 6.665 KG at 853 Amp. |
| Magnetic Length: | 51.64" |
| Inductance: | $L_s$ = 9.4mH at 1 KHz<br>Q = 8.4 |

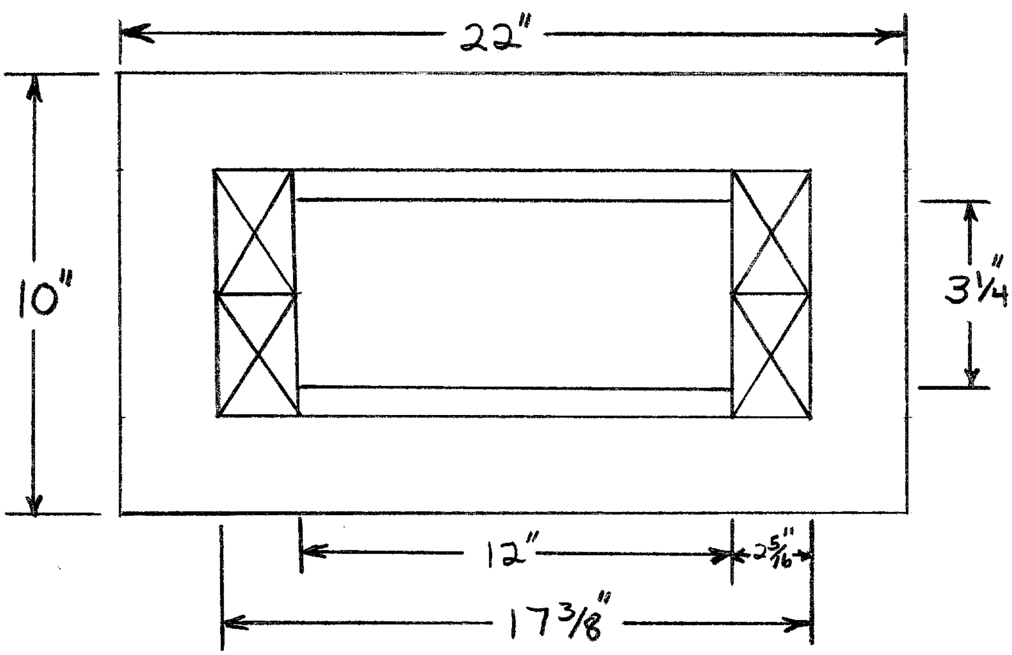


TABLE 2

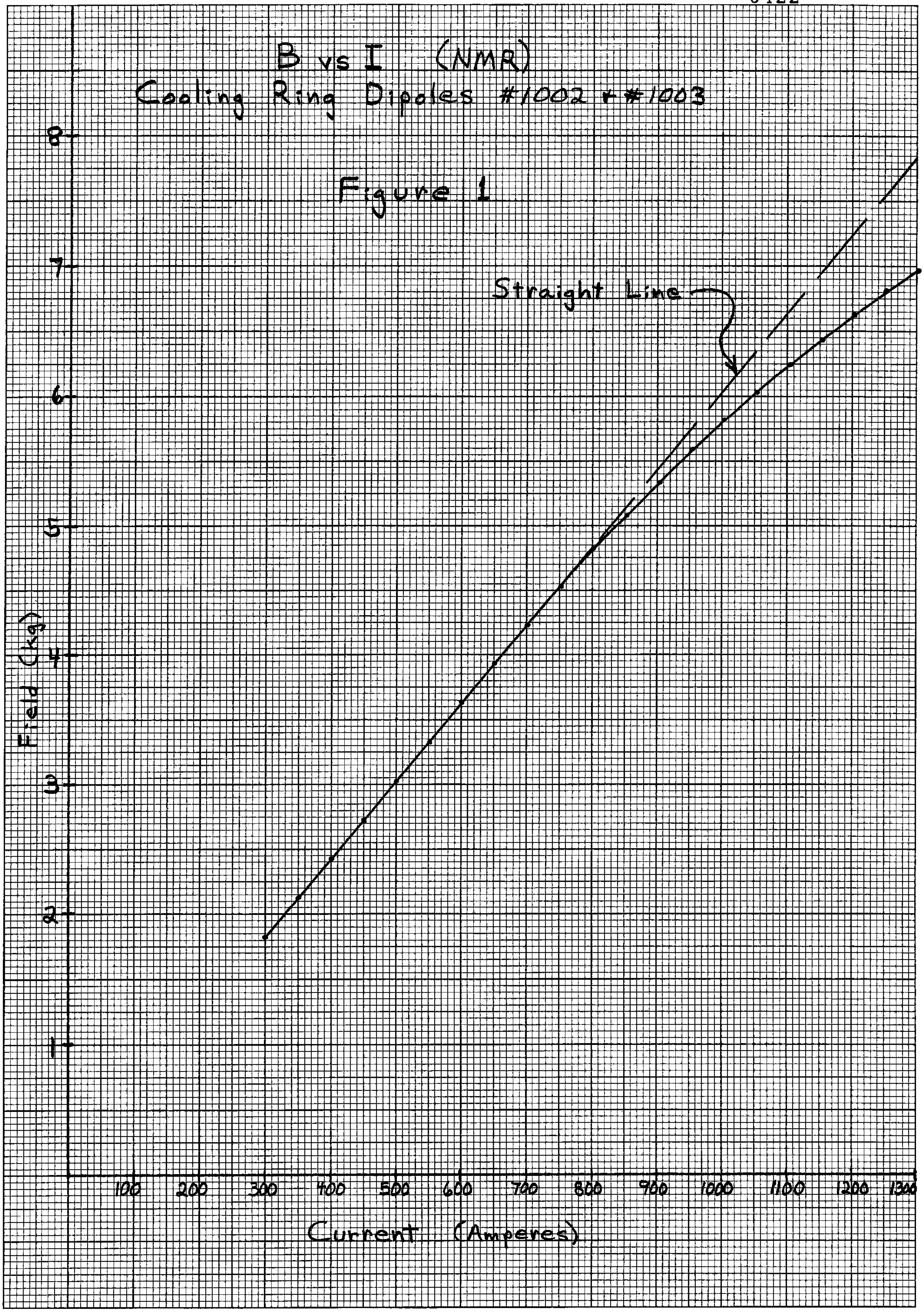
B vs I (NMR 18" inside magnets #1002 and #1003)

| CURRENT (Amperes) | FIELD (Gauss) | MAGNET #1003 TRANSFER FUNC. (Gauss/Ampere) | MAGNET #1002 TRANSFER FUNC. (Gauss/Ampere) |
|---|---|---|---|
| 301.4 | 1823.1 | 6.049 | 6.042 |
| 351.9 | 2127.9 | 6.047 | 6.041 |
| 401.7 | 2428.9 | 6.047 | 6.040 |
| 451.6 | 2727.5 | 6.040 | 6.039 |
| 502.2 | 3033.1 | 6.040 | 6.036 |
| 552.4 | 3335.6 | 6.038 | 6.035 |
| 602.6 | 3635.1 | 6.032 | 6.032 |
| 652.6 | 3934.2 | 6.029 | 6.029 |
| 703.2 | 4236.7 | 6.025 | 6.022 |
| 753.3 | 4531.3 | 6.015 | 6.013 |
| 802.9 | 4812.8 | 5.994 | 5.993 |
| 853.6 | 5085.8 | 5.956 | 5.958 |
| 904.0 | 5344.0 | 5.912 | 5.911 |
| 953.7 | 5596.0 | 5.868 | 5.855 |
| 1004.1 | 5818.8 | 5.795 | 5.794 |
| 1054.1 | 6037.8 | 5.728 | |
| 1105.1 | 6250.9 | 5.656 | |
| 1155.5 | 6447.5 | 5.580 | |
| 1204.7 | 6630.2 | 5.504 | |
| 1255.2 | 6807.3 | 5.423 | |
| 1305.5 | 6973.7 | 5.342 | |

TABLE 4

Integrated Field Shape at 5 KiloGauss

| X in. | 2 ft. search coil | Without End Shims Stretched Wire | With Final Shims Stretched Wire |
|---|---|---|---|
| -5.2 | -2.04 | -2.12 | -1.83 |
| -4.8 | - .76 | - .94 | - .66 |
| -4.4 | - .24 | - .46 | - .21 |
| -4.0 | - .06 | - .27 | - .06 |
| -3.6 | - .01 | - .18 | - .01 |
| -3.2 | .01 | - .12 | .00 |
| -2.8 | .01 | - .08 | .00 |
| -2.4 | .01 | - .06 | .00 |
| -2.0 | .00 | - .05 | - .01 |
| -1.6 | .00 | - .03 | - .01 |
| -1.2 | .00 | - .02 | .00 |
| - .8 | .00 | .00 | .00 |
| - .4 | .00 | .00 | .00 |
| 0.0 | .00 | .00 | .00 |
| .4 | .00 | - .01 | - .01 |
| .8 | .00 | - .01 | - .01 |
| 1.2 | .00 | - .01 | - .01 |
| 1.6 | .00 | - .02 | - .02 |
| 2.0 | .00 | - .03 | - .02 |
| 2.4 | .00 | - .05 | - .01 |
| 2.8 | .00 | - .07 | - .01 |
| 3.2 | .00 | - .10 | .00 |
| 3.6 | - .02 | - .16 | - .01 |
| 4.0 | - .07 | - .25 | - .05 |
| 4.4 | - .28 | - .44 | - .21 |
| 4.8 | - .88 | - .91 | - .64 |
| 5.2 | -2.29 | -2.07 | -1.78 |


B vs I (NMR)
Cooling Ring Dipoles #1002 + #1003
Figure 1
Straight Line
Field (kg)
Current (Amperes)
1
2
3
4
5
6
7
8
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300

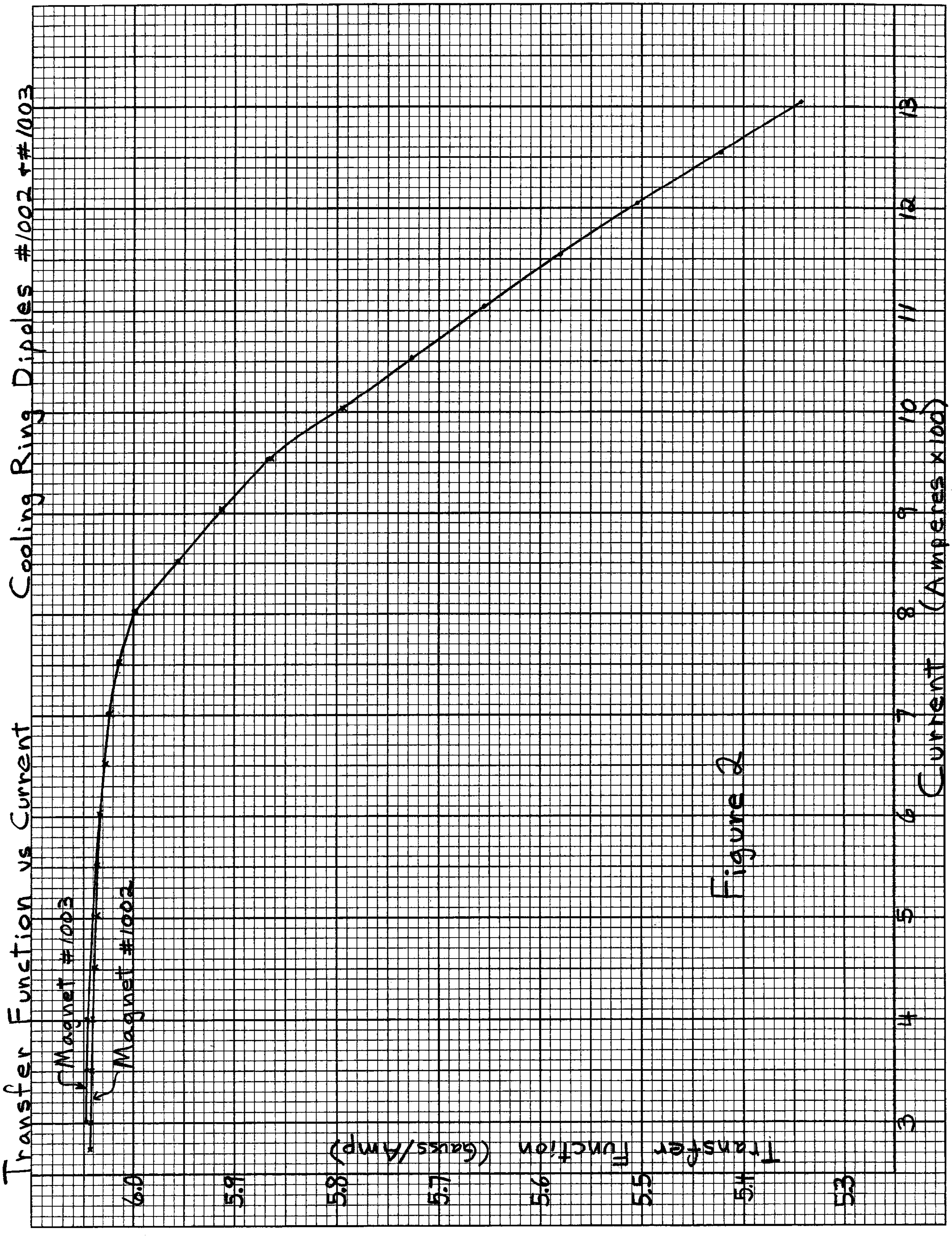
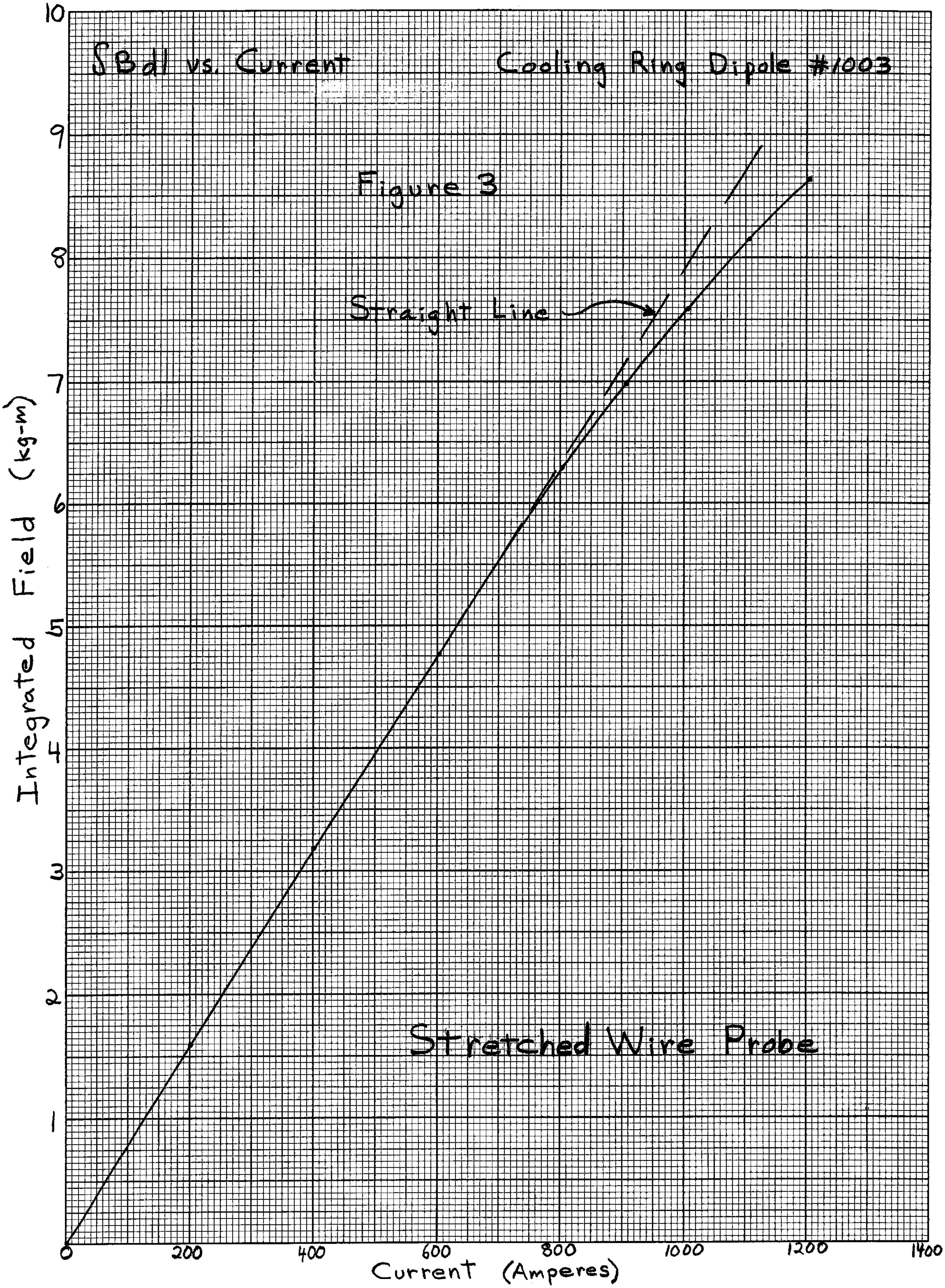
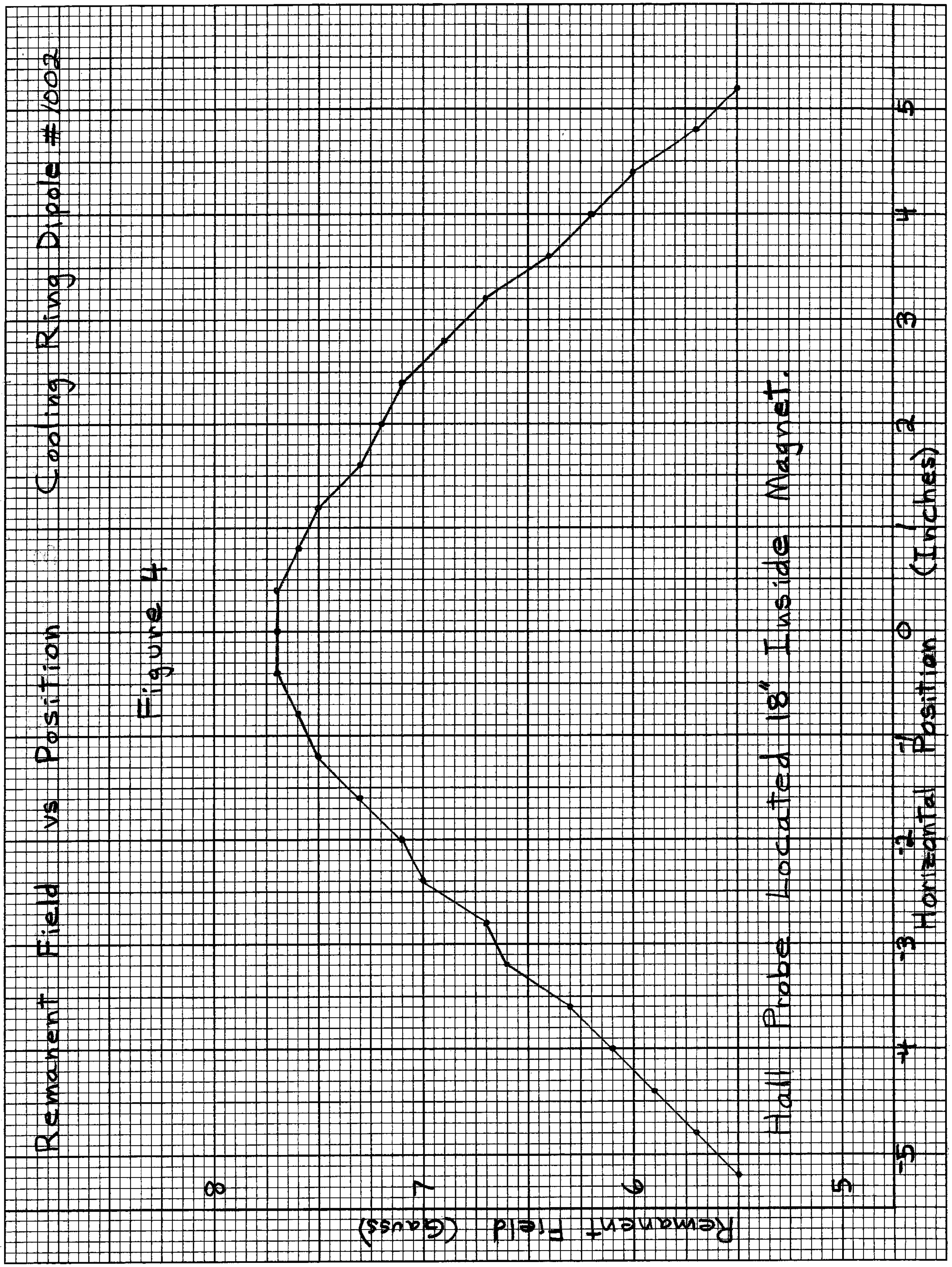
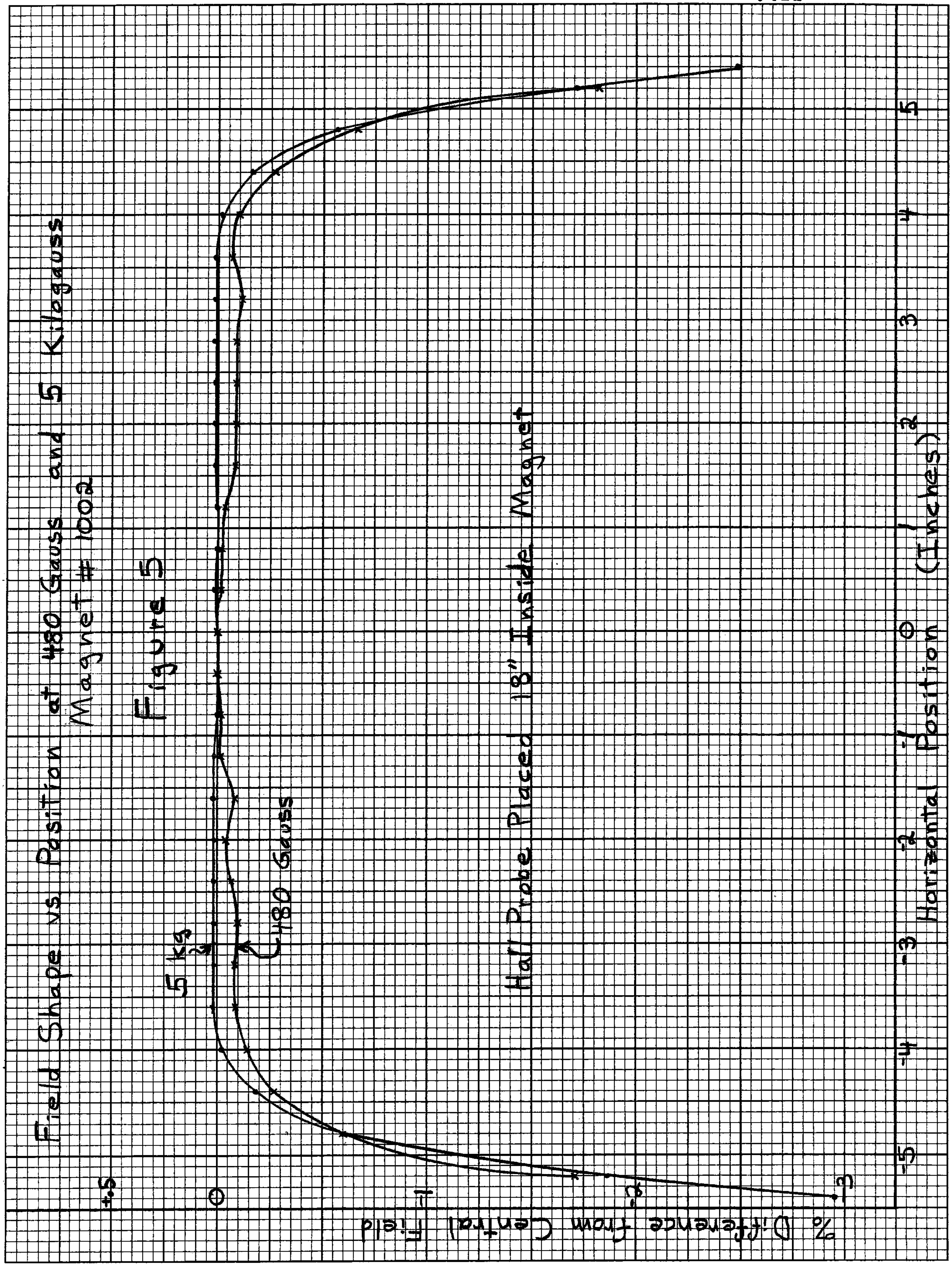

Transfer Function vs Current
Cooling Ring Dipoles #1002 + #1003
Magnet #1003
Magnet #1002
Transfer Function (Gauss/Amp)
6.0
5.9
5.8
5.7
5.6
5.5
5.4
5.3
Current (Amperes x100)
3
4
5
6
7
8
9
10
11
12
13

Figure 2


∫Bdl vs. Current
Cooling Ring Dipole #1003
Figure 3
Straight Line
Stretched Wire Probe
Integrated Field (kg-m)
Current (Amperes)
0
1
2
3
4
5
6
7
8
9
10
200
400
600
800
1000
1200
1400


Remanent Field vs Position
Cooling Ring Dipole #1002
Figure 4
Hall Probe Located 18" Inside Magnet.
Horizontal Position (Inches)
-5
-4
-3
-2
-1
0
1
2
3
4
5
Remanent Field (Gauss)
8
7
6
5


Field Shape vs Position at 480 Gauss and 5 Kilogauss
Magnet # 1002
Figure 5
Hall Probe Placed 18" Inside Magnet
5 kg
480 Gauss
Horizontal Position (Inches)
-5
-4
-3
-2
-1
0
1
2
3
4
5
% Difference from Central Field
+.5
0
-.1
-.2
-.3

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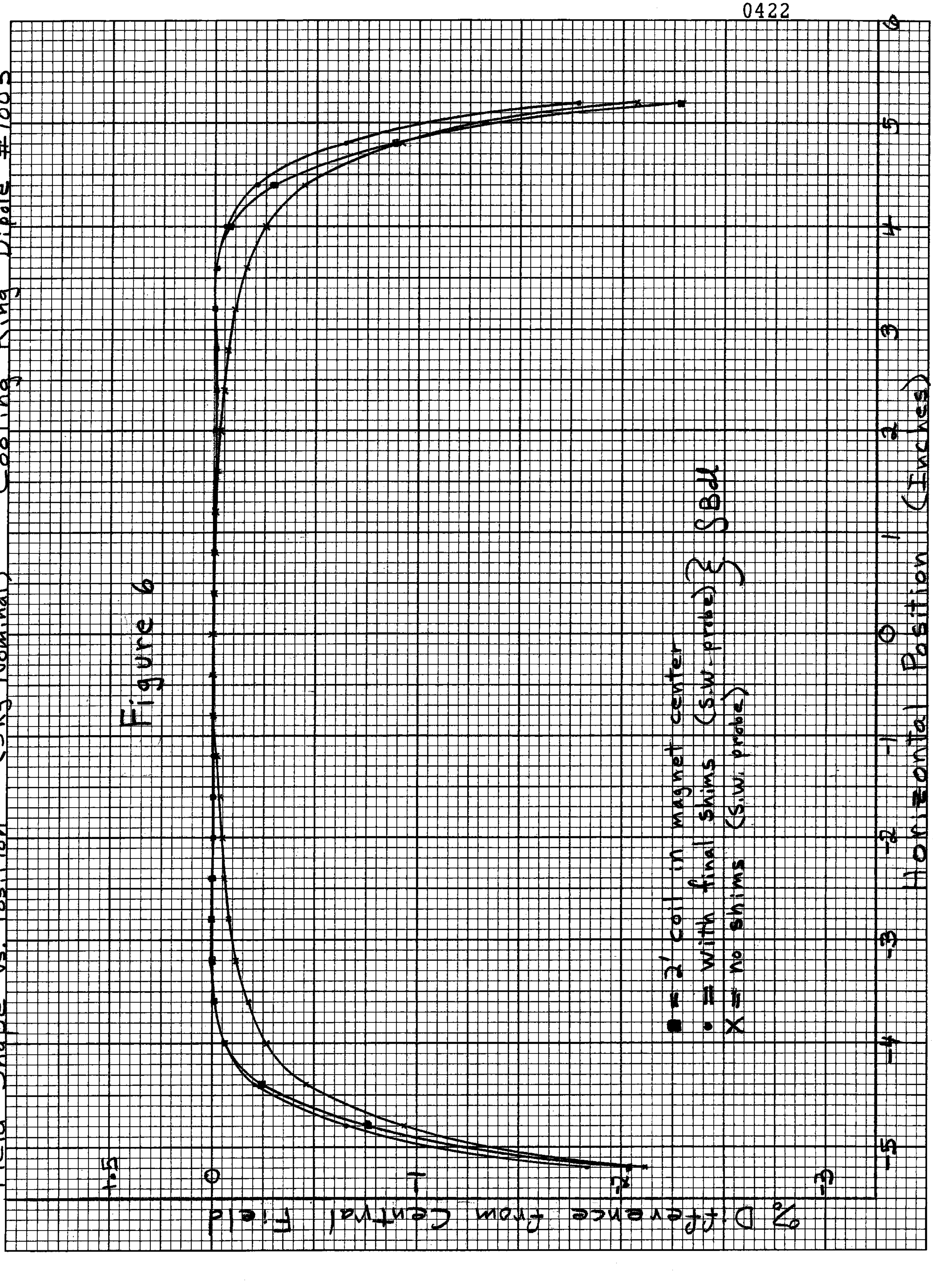
Field Shape vs. Position (5kg Nominal) Cooling Ring Dipole #1003
Figure 6
■ = 2' coil in magnet center
• = with final shims (S.W. probe)
X = no shims (S.W. probe)
∫Bdl
Horizontal Position (Inches)
% Difference from Central Field

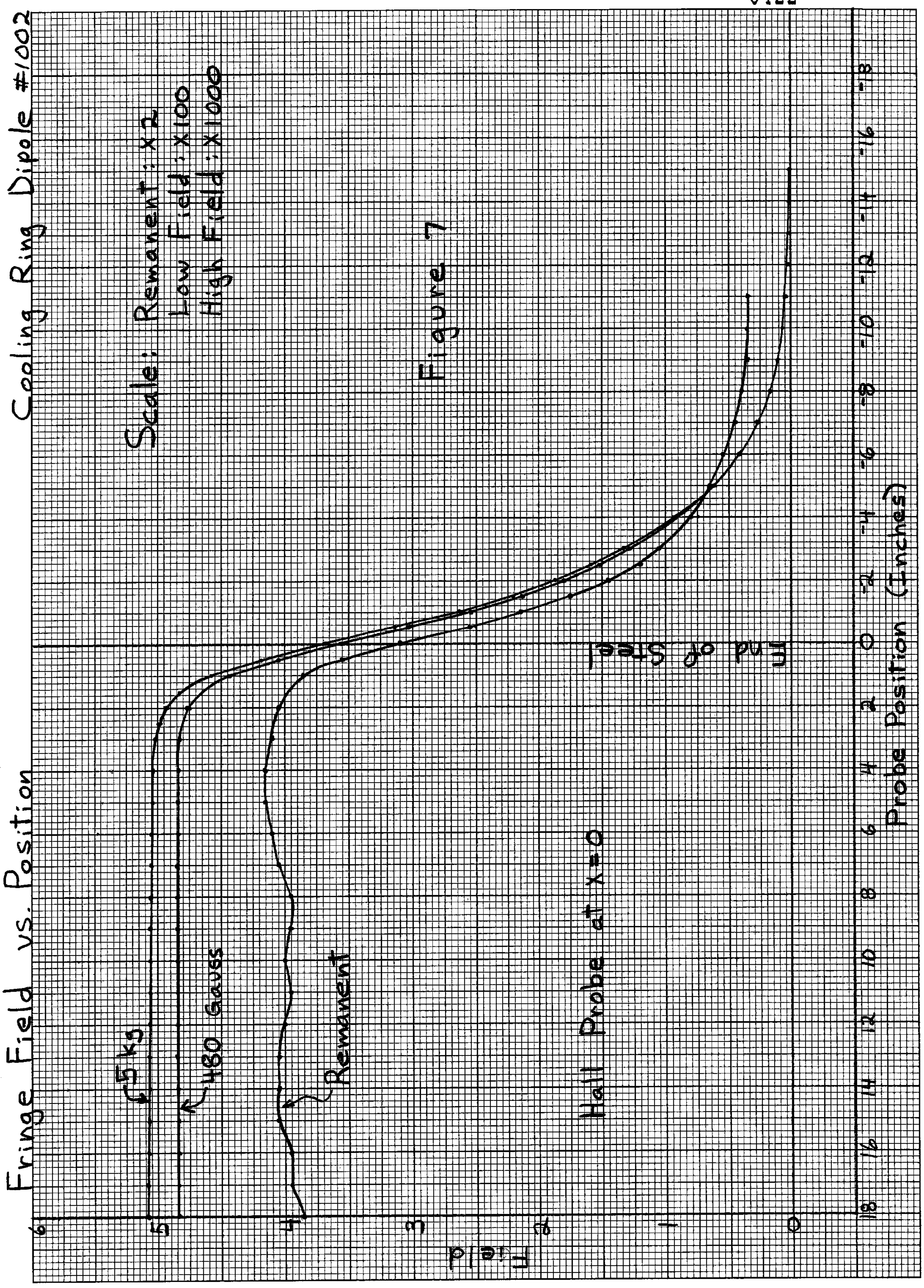
Fringe Field vs. Position Cooling Ring Dipole #1002
Scale: Remanent: X2
Low Field: X100
High Field: X1000
5 kG
480 Gauss
Remanent
Hall Probe at X=0
End of Steel
Field
6
5
4
3
2
1
0
Probe Position (Inches)
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18

Figure 7